LCA Methodology

Life Cycle Assessment of Water-based Acrylic Floor Finish Maintenance Programs*

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DOI: http://dx.doi.org/10.1065/lca2007.04.323

Please cite this paper as: Thabrew L, Lloyd S, Cypcar CC, Hamilton JD, Ries R (2007): Life Cycle Assessment of Water-based Acrylic Floor Finish Maintenance Programs. Int J LCA 13 (1) 65–74

Abstract

Aim, Scope, and Background. Industrial and institutional (I and I) floor maintenance activities require regular use of chemical products and equipment. Different floor care systems require different maintenance products, activities, and frequencies which consume different levels of energy and material for product manufacturing, maintenance, and application. Therefore, selecting between floor maintenance products and programs requires comprehensive analysis of the entire floor maintenance system as well as any site-specific factors that can influence human and environmental health. In this paper, a probabilistic model for comparing the environmental life cycle implications of I and I floor maintenance programs is presented. The primary interest is in comparing programs that use different water-based acrylic floor finishes and in particular, programs using zinc-containing floor finishes compared to zinc-free floor finish systems. Zinc, used in some acrylic polymers as a polymer cross-linking agent, is regulated in some communities to minimize its impact on the aquatic environment.

Method. The life cycle assessment (LCA) model was developed in compliance with the ISO 14040 series of standards [1]. Furthermore, uncertain input variables were defined as probabilistic distributions and Latin Hypercube Sampling was used to propagate uncertainty through the model. The scope of the study includes the full life cycle of the materials, supplies, equipment, and activities associated with performing floor maintenance. The effects of maintaining higher lighting and temperature levels while performing floor maintenance are estimated using building energy system analysis. The life cycle inventory (LCI) element of the LCA was developed using product-specific data, publicly available data, and established life cycle inventory databases. Life cycle impact assessment was conducted using the Eco-Indicator 99 [2] and Impact 2002+ [3,4] impact assessment methods.

Results. Two floor maintenance scenarios were developed and analyzed to compare the environmental impact of programs using zinc-containing and zinc-free floor finishes. The results discussed herein are presented for a hypothetical retail store located in the Midwest region of the United States. Given the scenarios examined, zinc-free floor finish systems reduced the release of zinc ions to the environment, but the overall impact in all life cycle impact assessment (LCIA) categories was greater for the zinc-free floor finish system primarily due to the increased frequency of maintenance.

Discussion. The impacts associated with operating the facility were orders of magnitude higher than those associated with producing or using floor care products, supplies, or equipment. This leads to the conclusion that for critical impacts, floor care product development should focus research efforts on innovative products that reduce application and maintenance time if significant reduction in these impacts is sought.

Conclusions. Adopting a stochastic modeling approach enabled incorporation of parameter uncertainty and analysis of uncertainty in model results. In the scenario shown here, the magnitude of overall impact in all LCIA categories was greater for the zinc-free floor finish system than the zinc-containing floor finish system.

Perspectives. Use of decision modeling software provided flexibility for developing scenarios and assessing floor maintenance programs under various operational and site-specific conditions.

Abbreviations: CARB – California Air Resources Board; CBECS – Commercial building energy consumption survey; CDF – Cumulative distribution function; CF – Characterization factor; DALY– Disability adjusted life year; DF – Damage factor; HVAC – Heating, ventilating, and air conditioning; ISSA – International Sanitary Supply Association

Keywords: Facility operations; floor maintenance; parameter uncertainty; water-based acrylic floor; zinc-free floor finish

Introduction

Industrial and institutional (I and I) floor maintenance programs, although conceptually similar, vary in actual practice. Maintenance programs vary substantially in terms of types and frequencies of floor maintenance activities, composition of cleaners, strippers, and finishes, and types and capacities of maintenance equipment. Energy, material, and human resources are required to perform floor maintenance. Efforts have been made to understand the risks from using and disposing floor care products. For example, Long and Baird [6] characterized the environmental impact of zinc introduced to the environment in wastewater streams from

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stripping and disposing zinc-containing floor finishes. This type of environmental risk assessment provides an understanding of the behavior of specific floor care constituents in natural systems and their influence on biological systems. The main focus of Life-Cycle Assessments (LCA) on flooring has been flooring material specific, and/or, floor care product specific [6–10]. In use-phase analysis carried out by Jönsson [8], the focus was on the emissions from using floor care products. A study of floor covering maintenance by Paulsen [6] captured product specific parameters such as frequency of occasional and regular maintenance, and service life of the floor covering to investigate floor care requirements. However, parameters implicitly related to floor maintenance, such as an increase in building services due to floor maintenance, were not included in the scope of these analyses.

Understanding and comparing the overall environmental impact of a floor maintenance program requires a system-based LCA model that can incorporate maintenance processes as well as building services. The potential product performance differences can alter the frequency, number, and type of maintenance activities resulting in different emissions and resource use. Therefore, to understand the consequences of floor maintenance programs and the tradeoffs between different program options, the entire life cycle of products and processes required for performing floor maintenance should be considered. This includes facility operations, e.g., the increased lighting, heating, and cooling energy used to ready the building for the floor maintenance process. This paper describes a model developed which includes not only the functional aspects of floor maintenance programs using zinc-containing and zinc-free floor finishes, but also the effects of building systems in order to provide a more comprehensive analysis of life cycle environmental impact.

Product-oriented LCA models are typically developed to evaluate the implications of a specific product or system for one or a defined set of scenarios. This LCA model has a simple user interface for selecting floor maintenance options and defining site-specific parameters. The interface allows a user to develop scenarios to assess the environmental impacts of different floor maintenance programs at different sites or evaluate the impacts of different floor maintenance options at one site.

In recent years, efforts have been made by life LCA practitioners to capture uncertainty and variability in LCA models [11–14]. One way to perform uncertainty analysis is to adopt a stochastic rather than a deterministic modeling approach. In this study, input parameters were defined as probabilistic distributions in most areas, and Latin Hypercube sampling was used to propagate uncertainty through the model. Process-based LCA techniques were used to develop the life cycle inventory (LCI) model. Life cycle inventory tables were developed using product-specific data, publicly available data, and established life cycle inventory databases. For example, inventory tables developed by the Energie-Stoffe-Umwelt group (ESU) and ETH Zürich and contained in the ETH-ESU library [15] were used to quantify the inputs and outputs associated with producing materials contained in floor care products, supplies, and equipment and energy required for performing floor maintenance. Using 1996 European data in U.S. conditions is an important limitation of this model. However, the key benefit of using the ETH-ESU library is that it provides a detailed and consistent life cycle inventory.

Numerous life cycle impact assessment (LCIA) methods have been developed to translate the inventory of inputs and outputs into potential environmental impact. Characterization and damage factors vary between LCIA models. The interpretation of results from different LCIA models may lead to contradictory conclusions [16]. To capture the variability between LCIA results, two impact assessment methods, namely, Eco-Indicator 99 [3] and Impact 2002+ [4,5] were used to evaluate potential environmental impact.

In summary, this paper presents a systematic modeling approach for incorporating parameter uncertainty in LCA, enabling site-specific scenario development, and interpreting uncertain LCA results. The modeling approach is applied to develop and evaluate site-specific floor maintenance programs. The primary interest is in comparing programs that use different water-based acrylic floor finishes and in particular, programs using zinc-containing finishes compared to zinc-free finish systems. Approaches for reducing the environmental impact of I and I floor care systems were identified.

1 Goal and Functional Unit

The goal of the project is to develop a life cycle model for comparing I and I floor maintenance programs and to conduct a comparative LCA of programs using zinc-containing and zinc-free floor finishes. The results of the comparative LCA will be used to compare the tradeoffs between zinc-containing and zinc-free floor finishes and associated maintenance programs. Maintaining floor appearance is the function or service that a floor maintenance program provides. The specific functional unit is maintaining the floor of a single facility over a one-year period. The reference flows, or flows necessary to perform annual floor maintenance, depend on the characteristics of the floor maintenance program and the facility. The system boundaries include all life cycle stages, such as raw material extraction and energy and material production, distribution, use, and disposal. While all materials, supplies, equipment, and activities associated with performing floor maintenance are considered, not all life cycle stages are evaluated for each. **Fig.1** provides an overview of the system boundaries and **Table 1** lists the products and processes for floor maintenance and identifies the specific life cycle stages considered for each. Additional information on the average use of energy and basic materials for floor care per m^2 and year are provided in **Table S1** (see **Annex**) as supplementary material.

Three high-level modules were constructed in the floor maintenance LCA model:

- Process module: incorporates information about the facility, maintenance program, equipment, and floor care products to estimate the material and energy requirements from performing floor maintenance for one year.
- Life Cycle Inventory module: quantifies life cycle material and energy requirements and quantifies the resulting

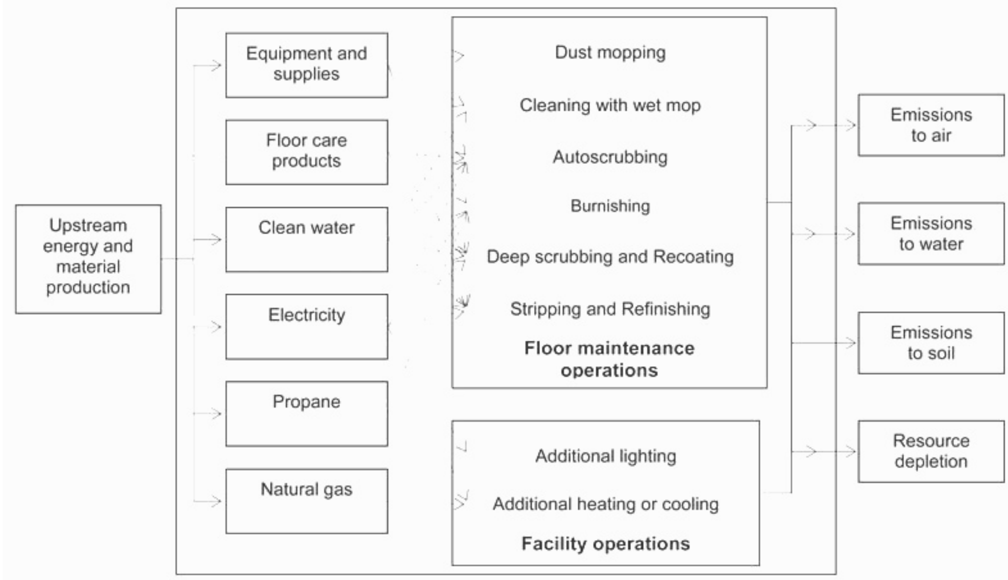

Fig. 1: The system boundary of the industrial and institutional floor maintenance model

Table 1: A check mark indicates that the life cycle stage of the product or process is included in the current LCA model

Product/process	Extraction	Manufacturing	Transport	Use	End-of-life	Unit
Electricity for operating facility	✓	✓	✓	✓	✓	kWh
Natural gas for operating facility	✓	✓	✓	✓	✓	m^3
Electricity for equipment	✓	✓	✓	✓	✓	kWh
Propane for burnishing	✓	✓	✓	✓	✓	m^3
Floor care products – cleaning solution 1	✓	✓		✓		m^3
Floor care products – cleaning solution 2	✓	✓		✓		m^3
Floor care products – stripper		✓		✓		m^3
Floor care products – finisher	✓	✓		✓		m^3
Treated water	✓	✓	✓	✓		m^3
Steel for autoscrubbers, burnishers, mop handles, putty knives, and scrapers	✓	✓		✓		kg
Aluminum for autoscrubbers and burnishers	✓	✓		✓		kg
Rubber for autoscrubbers, burnishers, and squeegees	✓	✓		✓		kg
Wood for mop handles	✓	✓		✓		kg
Cotton for dust and wet mop heads	✓	✓		✓		kg
Nylon for autoscrubber green pads, finish mop and straight broom heads	✓	✓		✓		kg
Polyester for burnisher pads and finish mops	✓	✓		✓		kg
Polyvinyl chloride for mop and straight broom handles, buckets, wringers, dust pans, and floor signs	✓	✓		✓		kg
Polypropylene for autoscrubber black pads, autoscrubber battery, strip mop heads, and doodlebugs	✓	✓		✓		kg
Polyethylene for battery autoscrubber, burnisher, and autoscrubber battery	✓	✓		✓		kg
Lead for autoscrubber battery	✓	✓		✓		kg
Sulfuric acid for autoscrubber battery	✓	✓		✓		kg
Copper for autoscrubber battery	✓	✓		✓		kg
Glass for autoscrubber battery	✓	✓		✓		kg

waste and environmental discharges from performing floor maintenance as defined in the process module.
- Life Cycle Impact Assessment module: incorporates environmental impact categories, category indicators, characterization models, and equivalency factors for estimating the potential effects of the emissions and resource use quantified in the LCI on human health and the environment.

Each module contains nested sub-modules that define input parameters, model the underlying relationships between these parameters, and calculate results.

1.1 System modeling and process modules

The process module estimates material and energy requirements by linking together four sub-modules, which include information related to the facility, maintenance program, equipment, and floor care product constituents.

(a) **Facility profile sub-module**: contains information about a facility, such as the amount of cleanable floor surface area and aisle width, electricity and natural gas use rates, and the estimated fraction of total electricity and natural gas use for maintaining the lighting and heating, ventilating, and air-conditioning (HVAC) systems while performing floor maintenance.

Energy use in buildings varies with respect to business activity and location. The Commercial Building Energy Consumption Survey (CBECS) [17] provides information on building energy use categorized by principal building activity and census region. For the scenarios considered herein, triangular distributions, shown in **Fig. 2**, were fit to the electricity and natural gas use rates for buildings with 'retail' as the primary building activity in the 'Midwest' census region.

Maintenance activities are commonly conducted at night. Building services are commonly 'set back' when the building is not occupied. For example, only safety and security lighting may be left on, heating set point temperatures may be reduced in the winter, and cooling set point temperatures may be increased in the summer. This 'setback' state saves energy. When building maintenance activities are conducted, building services are set at or close to their occupied condition. If a store is normally closed when maintenance occurs, the difference between energy consumed at an occupied condition and energy consumed at a 'setback' state is allocated to floor maintenance activities. In the model, if a store is open 24 hours per day, no building services are allocated to floor maintenance. Building energy allocated to maintenance was determined in the following way. Annual electricity and natural gas use for two occupancy profiles were estimated using building energy simulation software [18]. In one case, the occupied settings for operating building systems were used only during business hours and setback conditions were used at all other times. In the second case, the occupied conditions were used during business hours and during the times floor maintenance activities occurred. The difference in electricity and natural gas use in these two use profiles represents the energy used to maintain occupied conditions during floor maintenance activities. A ratio representing the energy use reduction is calculated and multiplied by the average hourly electricity and natural gas use derived from CBECS to determine the building service-related energy use for each hour of floor maintenance activity.

(b) **Maintenance program sub-module**: includes nested activity sub-modules for six floor maintenance activities.

- Dust mopping: includes walking the floor with a dust mop and using a putty knife to remove gum and stickers. Dust mopping is done before most other tasks, such as cleaning.
- Cleaning with wet mop: includes cleaning the floor with a mop, a bucket, and water with cleaning solution.
- Cleaning with autoscrubber: includes cleaning the floor with an autoscrubber, wet mop, and cleaning solution. Wet mopping is used in areas, such as corners, that cannot be reached with the autoscrubber.
- Burnishing: includes burnishing the floor to increase the glossy appearance of a floor and dust mopping after burnishing.
- Deep scrub and recoat: includes deep cleaning the floor with an autoscrubber to remove the top layers of floor finish and reapplying floor finish with a finish mop.
- Strip and refinish: includes applying stripper to the floor with a strip mop, using an autoscrubber and a mop to remove the finish from the floor, and refinishing the floor by applying floor finish with a finish mop.

This sub-module defines the floor maintenance schedule, identifies the equipment used to perform floor maintenance, and calculates the annual amount of energy, water, equipment material and floor care product required to perform each floor maintenance activity. Specific floor maintenance activity types and their frequencies were based on floor

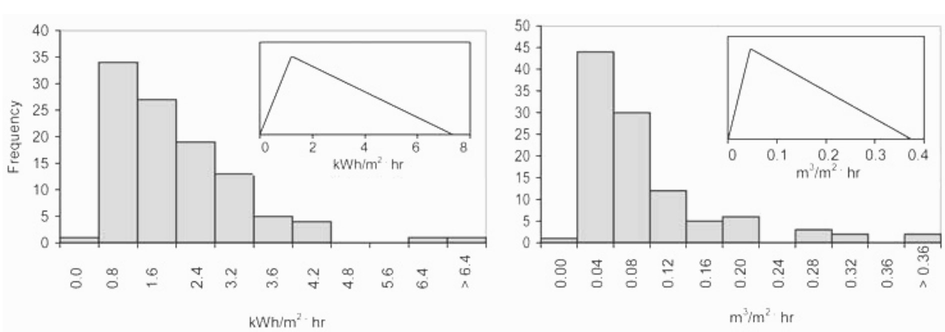

Fig. 2: Frequency histograms and the respective triangular distribution approximations for the building-related electricity and natural gas use rates in the example maintenance scenario

maintenance manuals [19]. This sub-module also calculates the fraction of each equipment's life associated with performing floor maintenance activities for the study period.

(c) **Equipment and material sub-module**: includes equipment specifications, e.g., power source, capacity, and efficiency, and information about the useful lifetimes and main materials of each type of equipment and ancillary products. For some types of equipment, multiple options exist, and the user can specify the number of each type used. For certain options, a percentage of each type can be specified. For example, mops can be cotton, nylon, or polypropylene, and can have steel, wood, or plastic handles. In addition to the materials used, these options also affect their useful lifetimes.

The maintenance model includes equipment types and models which are commonly used in I and I facilities. The equipment productivities were estimated using ISSA's 358 Cleaning Times [20]. The productivities give the rate at which a floor can be dust mopped, wet mopped, autoscrubbed, burnished, stripped and refinished. The guide was also used to derive productivities for equipment with different performance characteristics, such as battery and electric autoscrubbers, and propane and electric burnishers. The productivities were graphed for available pad sizes and revolutions per minute (rpm), and using trends, the adjusted productivities were established for the different pad sizes of the equipment models. Overall equipment efficiencies, which include internal combustion engine efficiencies, autoscrubber battery charging and discharging efficiencies, and brush, vacuum, and traction motor efficiencies respectively were estimated using Hoffert et al. (2002) [21].

(d) **Solution constituents and water sub-module:** comprises information on floor care product ingredients, dilution ratios, and zinc levels in municipal water. Floor care products used in typical floor maintenance programs include cleaning solutions, strippers, and finishes. The solution coverage rates determine the volume of floor care product used in deep scrubbing, stripping or refinishing a floor. They were derived using [20].

1.2 Life cycle inventory module

LCI results are quantified for (a) the energy to operate the facility; (b) the equipment and supplies to perform floor maintenance, and (c) the floor care products to clean, strip, and finish the floor. This includes aggregated emissions and resource use for generating electricity to operate the facility, treat and distribute water, recharge battery-powered autoscrubbers, and run corded electric burnishers; producing and using natural gas to operate the facility; producing and using propane to operate propane powered burnishers; producing materials for equipment and supplies, and disposing floor care products. The LCI module quantifies nearly 400 inventory categories for some of the products and processes considered.

(a) **Life cycle inventory calculations using ETH-ESU data:** The floor maintenance LCA model assumes that resource inputs and emissions are linearly related to production or processing levels. Inventory tables from the ETH-ESU library are used to quantify resource inputs and environmental releases associated with providing electricity, natural gas, propane, and the materials that are used in equipment and supplies. For each of these, inventory tables from a minimum of three comparable processes were used to fit triangular distributions for the process inputs and releases. The minimum, mean, and maximum values from the available inventory tables were used as the distribution parameters. For floor care product manufacturing, the chemical manufacturing processes and water treatment and distribution energy use are used to develop the life cycle inventory.

(b) **Electricity mix estimation using the U.S. Department of Energy state electricity profiles:** To estimate resource use and emissions from producing electricity, it is necessary to define an electricity mix that characterizes the energy production in a region. Data on electricity generation by primary energy source from the U.S. Department of Energy's State Electricity Profile 2002 were used to develop appropriate electricity mixes for the Midwest region [22]. For each primary energy source, triangular distributions were established using the minimum, mean, and maximum amount of electricity generated with each type of generation method for each state within the region. These values are used in the probabilistic simulation to derive an energy mix.

(c) **Emissions from using and disposing of floor care products:** Volatile organic compound (VOC) releases to air from using floor care products are estimated by assuming that all of the constituents classified as California Air Resources Board (CARB) and non-CARB VOCs released during use. It is assumed that 100% of the VOCs evaporate to air. Also included are VOC released during propane combustion during burnishing. Zinc ion content in the floor care products were estimated using information provided by the manufacturer. A triangular distribution was established from the low, average, and high zinc content estimates. It is further assumed that all the floor finish required for the site is consumed and released to wastewater in the ionic form after stripping the floor. This allows the model to use the amount of floor finish consumed as a proxy for the amount disposed.

Zinc releases to water from disposing water used during floor maintenance (i.e., water used rinse or to prepare cleaner solution from concentrate on-site) are estimated using publicly available water quality reports. The model assumes that all water used for floor maintenance is disposed of at the end of cleaning activities and zinc in the water is in ionic form. A uniform distribution was established using the upper and lower zinc content found in publicly available water quality reports [23].

(d) **Municipal water treatment:** The amount of energy required to treat and distribute water is estimated based on Pittsburgh Water and Sewer Authority data (personal communication, Dr. Stanley States, Pittsburgh Water and Sewer Authority, October, 2004). A uniform distribution with an upper and lower limit 20% above and below the mean estimate is used.

1.3 Life cycle impact assessment module

The LCIA module uses two impact assessment methods: 1) Eco-Indicator 99 and 2) Impact 2002+. The damage factors (DF) and characterization factors (CF) provide a numerical score for impact estimates in the broad categories of human health, eco-toxicity, and resource depletion. Impact assess-

ment considers the full inventory in terms of both facility-related and maintenance-related activities. The impact is calculated based on the unit emissions to air, water and soil, and the calculations are as specified by the methods.

1.4 Scenario development and characteristics of the example scenario

The following features of the user interface assist with scenario development: i) an option to define a facility profile and a maintenance schedule; ii) an option to perform cleaning with a wet mop only rather than with an autoscrubber, i.e. some facilities use a wet mop to perform daily cleaning while other facilities use both a wet mop and an autoscrubber; iii) autoscrubber and burnisher options that allow the user to select between battery or corded electric autoscrubbers and between propane or corded electric burnishers as well as different equipment models in these categories; iv) an option to define chemical constituents in floor care products; and, v) input and output nodes that provide a simple user interface that allow the user to change the values of input variables and view results.

The following scenario demonstrates the features of the model, and is used for the example results discussed in the paper. The scenario consists of a retail store chain located in the Midwest region of the U.S where: i) the model parameter ranges encompass all stores of this chain in this region; ii) the mean cleanable floor surface area is 4,200 m^{2-}; iii) the store opening hours vary between 7 am to 10 pm, and cleaning takes place after the store closes for the day; iv) the maintenance schedule includes daily dust mopping and cleaning with an autoscrubber, burnishing three or four days per week depending on other activities, deep scrubbing and recoating twice per stripping period, and stripping and refinishing every twelve months for the zinc-containing floor finish system and every nine months for the non-zinc floor finish system; v) a 32 inch battery-powered autoscrubber is used for cleaning, and a 24 inch propane-powered burnisher is used for burnishing. Stochastic modeling was performed using Latin Hypercube simulation with 1,000 iterations. The principal parameter estimates used for the scenario is summarized in **Table 2**.

2 Results and Discussion

The Eco-indicator 99 and Impact 2002+ impact categories and results are shown in Table 3. These results are the sums from all processes, equipment, supplies, and floor care products that are used or generated over the life-cycle of floor maintenance programs, including material extraction through to end-of-life. **Fig. 3** illustrates the values corresponding to the electricity use for the zinc-free and zinc-containing floor finish systems calculated using the model. The model results can be viewed separately with respect to 'Facility Operation' and 'Maintenance Activities', where facility is the building-related requirements for heating, cooling and lighting, and maintenance is derived from the actual use of products and performing the maintenance tasks. Compared to direct floor maintenance activities, facility operations result in higher electrical energy consumption, and also higher uncertainty as shown by the box-and-whisker plots. Furthermore, the model interface displays CO_2 emissions, zinc emissions, VOC emissions, water use, natural gas use, pro-

Table 2: Selected parameter estimates used in the example scenario

Parameter name	Value	Units	Description and notes
Cleanable surface	Uniform(1660, 6500)	m^2	Approximate cleanable surface area of the store, modeled as a uniform distribution. If the exact floor space is known, the exact value is entered for both the lower and upper ends of the range.
Facility electricity use rate	Triangular(0.00021202, 0.0245245, 0.1514225)	$kWh/m^2 \cdot hr$	Estimated amount of electricity used to operate the facility, derived from Commercial Buildings Energy Consumption survey (CBECS) data using entries with retail as the primary business activity.
Facility natural gas use rate	Triangular(0.00000578, 0.0027068, 0.02177912)	$m^3/m^2 \cdot hr$	Estimated amount of natural gas used to operate the facility, derived from Commercial Buildings Energy Consumption survey (CBECS) data for the entries with retail as the primary business activity.
Dust mopping times per year	365	none	Number of times the floor is dust mopped per year. Assumes the dust mop is passed over the entire cleanable floor surface once during each scheduled dust mopping.
Cleaning with autoscrubber and wet mop times per year	298	none	Number of times the floor is cleaned with an autoscrubber and wet mop. Assumes the autoscrubber and wet mop (in areas that cannot be cleaned with the autoscrubber) are passed over the entire cleanable floor surface once during each scheduled cleaning.
Burnishing times per year	200	none	Number of times the floor is burnished per year. Assumes the burnisher and a dust mop are passed over the entire cleanable floor surface once during each scheduled burnishing.
Deep scrub and recoat times per year (zinc)	2	none	Number of times the floor is scrubbed and recoated per year when a zinc-containing floor finish is used.
Deep scrub and recoat times per year (zinc-free)	5.33	none	Number of times the floor is scrubbed and recoated per year when a non-zinc floor finish is used.
Strip and refinish times per year (zinc)	1	none	Number of times the floor is stripped and refinished per year when a zinc-containing floor finish is used.
Strip and refinish times per year (zinc-free)	1.33	none	Number of times the floor is stripped and refinished per year when a non-zinc floor finish is used.

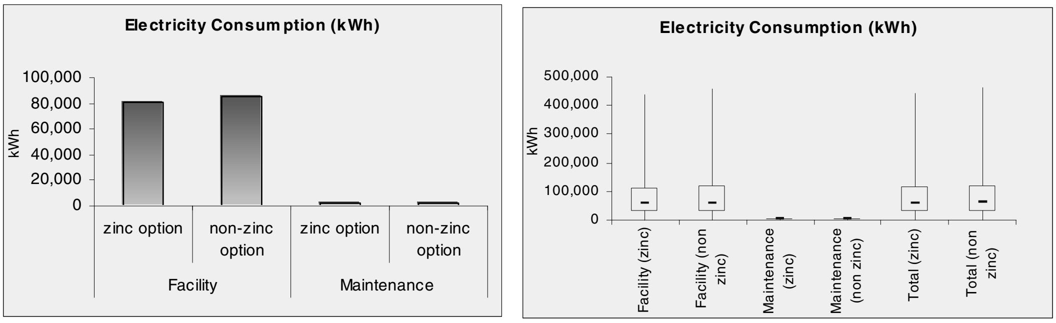

Fig. 3: Mean values and box-and-whisker diagrams for the facility and maintenance related electricity consumption based on the example maintenance scenario

pane use, and associated facility and maintenance activities for any given scenario. The software allows for easy addition of other categories as well.

The results of an analysis of the effects of the uncertainty in four variables on the total uncertainty in the facility-related CO_2 inventory are shown in **Fig. 4**. The bar height indicates the uncertainty range, i.e., the minimum value of facility-related CO_2 inventory subtracted from the maximum value of facility-related CO_2 inventory. Naturally, the uncertainty range is largest when all four variables are modeled as distributions and lowest when all four variables are modeled deterministically using their mean values. For this scenario, cleanable floor area and building energy use rates have the largest effect on uncertainty. Combined, the uncertainties in these two variables are responsible for about 90% of the uncertainty with respect to facility related CO_2 inventory. A similar analysis was done for floor maintenance activities, where uncertainty in the CO_2 inventory is caused mainly by the uncertainty in equipment energy use, equipment life spans, and upstream material and water production.

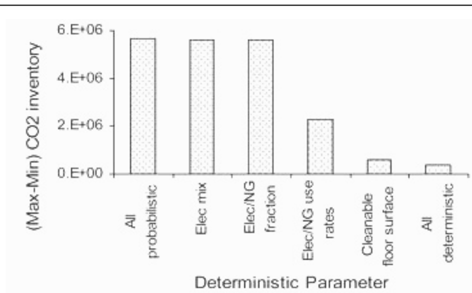

Fig. 4: Sensitivity analysis of the parameter contributions to overall uncertainty in CO_2 emission inventory for the example maintenance scenario

Given that the model parameters are in probabilistic terms, the results can be shown as a cumulative distribution function (CDF). Graphing the CDFs for the alternatives together indicates whether there is dominance of one alternative. If a CDF is above and to the left of another throughout the probability range, it is dominant. This way of presenting uncertain results is important, because when there is dominance by an alternative, it allows for interpretation of the results although the total uncertainty is large. **Fig. 5** shows the CDFs for the inventory results for CO_2, total VOCs, and zinc releases to water in which either zinc or zinc-free finish systems are dominant.

Table 3 shows the mean values for both Eco-Indicator 99 and Impact 2002+ impact assessment methods. These are the sums from all processes, equipment and supplies, and floor care products that are used or generated over the life-cycle of floor maintenance programs, including material extraction through to end-of-life. In general, the scores in similar categories in these two methods are in good agreement, as are the trends when comparing zinc and zinc-free floor finish systems. Some differences to note are the substantially higher disability adjusted life year (DALY) values for carcinogens in Eco-Indicator 99 compared to other categories in Eco-Indicator 99; the carcinogen category in Impact 2002+ is not as dominant. The non-carcinogen category in Impact 2002+ is the principal impact relative to other DALY-denominated categories in Impact 2002+. Given the assumptions and data used in this analysis, under the Impact 2002+ method, 90% of the mean value of the carcinogen impact is related to the manufacturing of cleaning equipment and supplies such as disposable cleaning tools, mops, and pads. Nine percent of the carcinogen score is related to facility operations and the remainder is associated with the use of the cleaning equipment. Similarly, most of the non-carcinogen score is related

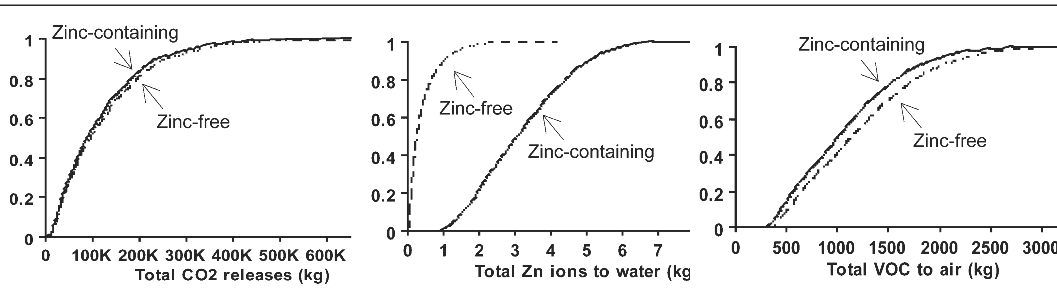

Fig. 5: Cumulative distribution functions for total CO_2, Zinc, and VOC releases show the results of the alternatives over the probability range for the example maintenance scenario

Table 3: Results for the example floor maintenance program scenario showing impact categories, units, and scores for the Eco-indicator 99 and Impact 2002+ impact assessment methods

Category	Unit	Eco Indicator 99		Unit	Impact 2002+	
		Zinc	Zinc-free		Zinc	Zinc-free
Carcinogens	DALYs	25.29	26.18	DALYs	0.0137	0.0142
Non-carcinogens	DALYs	–	–	DALYs	0.44	0.45
Respiratory inorganics	DALYs	0.040	0.042	DALYs	0.081	0.085
Respiratory organics	DALYs	0.00033	0.00038	DALYs	0.00035	0.00040
Global Warming Potential	DALYs	1.95	2.06	–	–	–
Global Warming Potential	–	–	–	kg CO_2 eq	136,400	143,700
Radiation	DALYs	0.00023	0.00024	DALYs	0.0013	0.0014
Ozone Depletion Potential	DALYs	0.000027	0.000028	DALYs	0.000027	0.000028
Ecotoxicity [a]/Toxic Emissions	PDFm^{2}yr	732,400	762,200	PAFm^{2}yr	494,900	516,500
Acidification and Eutrification [b]/Terrestrial Acidification and Nutrification	PDFm^{2}yr	1,900	2,000	PDFm^{2}yr	1,900	2,000
Aquatic Acidification	–	–	–	kg PO_4-eq	1,734,000	1,759,000
Terrestrial Eutrification	–	–	–	kg SO_2 eq	18	19
Resource Depletion (Energy)	MJ	136,000	142,600	MJ	2,343,000	2,459,000
Resource Depletion (Minerals)	MJ	–	–	MJ	847	874

[a] Impact 2002+ ecotoxicity category includes aquatic and terrestrial ecosystems combined
[b] Eco Indicator 99 includes combined effect of acidification and eutrification excluding aquatic ecosystems

to cleaning equipment and supplies manufacturing, which represents over 99% of the mean value of the non-carcinogen score in Impact 2002+. The breakdowns in these impact areas are similar for the Eco-Indicator 99 method.

The impacts of indoor emissions were examined within the framework of the Impact 2002+ method. For the human health category, Impact 2002+ uses intake fraction, or the fraction of an emission release that a human ingests through multiple pathways, in the impact calculation. The inhalation pathway was investigated for in-store maintenance activities for substances in the floor care products. A box model of the typical store was created, and, assuming that the store would be closed during maintenance, only the maintenance workers were exposed and that the ventilation rate is 1 L/s m^2 [24]. Given these assumptions, the intake fraction is 1.4 10^{-4}, which is 2 or more orders of magnitude greater than typical outdoor intake fractions in Impact 2002+. However, because of limited chemical effect data, the impact could not be calculated with Impact 2002+ for the specific constituents in the floor care products.

Fig. 6 shows the CDFs for global warming potential (GWP) and eco-toxicity for the Impact 2002+ method. The zinc-containing option has lower GWP and eco-toxicity compared to the zinc-free option. The dominance is not clearly represented in some of the CDFs due to the scale of the graph relative to the difference between the zinc and zinc-free options in the scenario. In terms of mean GWP values, processes related to heating, cooling and lighting the facility represent 82%, floor care product manufacturing, including cleaners, strippers, and finishes represents 10%, and floor care equipment manufacturing, including both powered and hand tools represents 8% of total GWP. In terms of eco-toxicity, the primary contributions to the overall score are from manufacturing floor care equipment.

3 Conclusions and Perspectives

A life cycle assessment model with input variables easily accessible to the user was developed to estimate the environmental life cycle implications of I and I floor maintenance programs. In particular, the model compares programs that use zinc-containing floor finishes to those using zinc-free floor finishes while taking into account concurrent facility operations. The modeling approach adopted in the assessment provides greater flexibility for developing scenarios and assessing the floor finish systems under various operational and regional conditions. Adopting a stochastic approach with Latin Hypercube sampling has enhanced the interpretation of model out-

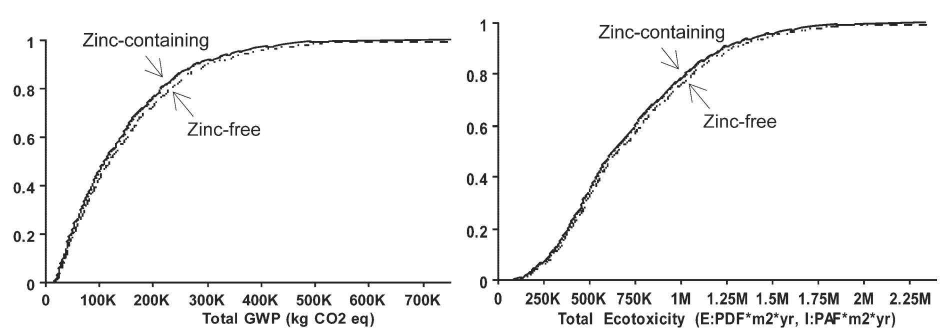

Fig. 6: Although the differences appear small on the graph, the cumulative distribution functions for the Impact 2002+ Global Warming Potential and Eco-toxicity impact categories show the dominance of the zinc-containing floor maintenance program in the example maintenance scenario

puts over a wider scale of parameter combinations. CDFs of impact categories allow the decision maker to evaluate alternatives with variable input parameters although overall uncertainty may be large. Apart from comparing the floor finish types, the model can compare the use of alternative types of equipment, which affect environmental impact through efficiency, performance, and energy options. The current model provides the scope and flexibility to identify improvement options and strategies for the product manufacturers, such as cleaning chemicals, equipment designs, and reducing maintenance time, which could contribute significantly towards lowering environmental impact. The current model also provides facility managers a tool for estimating the impact of their site-specific maintenance programs, as well as a tool for developing new programs. When using the model for a particular facility, the following parameters can be further refined to suit the specific conditions: cleanable surface area, annual electricity and natural gas rates, and the regional electricity generation mix. However, there will still be variability and uncertainty in the model, e.g., the inherent variability in emissions from electricity generation.

There are several limitations regarding the model development. The first key limitation is that several products and processes such as transporting and disposing of equipment and supplies required for performing floor maintenance have not been incorporated in the model, which will increase inventory results. The second involves determining the fraction of total electricity and natural gas use from facility operation that should be assigned to floor maintenance. In the scenarios developed here, energy modeling was conducted in order to estimate the facility operation energy requirements required for floor maintenance which considerably reduced the uncertainty associated with the parameter. Third, the current model's life cycle inventory is based on 1996 generic inventory data. The ETH-ESU inventory library is based on life cycle studies conducted to evaluate European products and processes rather than those in the United States, with the benefit of having nearly 400 consistent inventory categories for the subsequent impact assessment. Fourth, the impact assessment methods consider a limited number of impact categories, and not all categories are treated with equal thoroughness. Lastly, the model currently assumes sequential maintenance activities and does not consider the possibility of multiple floor maintenance activities occurring at the same time.

The model developed in this study found that energy use rates, cleanable floor area estimates, and the regional electricity mix are significant in the results. The model has provided opportunities to identify improvement options and strategies for the product manufacturer, particularly reduction in maintenance time, which contribute far more significantly towards lowering environmental impact than the presence or absence of zinc. Specifically, the presence or absence of zinc has on average less than a 5% difference in the LCIA categories. Overall, environmental impact is best reduced by improving the performance of the floor care system relative to the application time and application frequency. While zinc-free floor finish system improvements continue to emerge, the results of this study indicate that floor maintenance programs can contribute more significantly to reducing environmental impact by responsibly optimizing maintenance routines, than by focusing exclusively on using zinc-free floor finishes.

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Received: July 3rd, 2006
Accepted: April 25th, 2007
OnlineFirst: April 26th, 2007

Annex

Table S1: Material and energy use inventory per unit cleanable floor area and year for the principal elements of the industrial and institutional floor maintenance program life cycle assessment model

Item		Units	Floor finish system	
			Zinc-containing	Zinc-free
Facility electricity use		$kWh/m^2 \cdot yr$	20.18	21.19
Facility natural gas use		$m^3/m^2 \cdot yr$	4.33	4.55
Equipment electricity		$kWh/m^2 \cdot yr$	0.61	0.63
propane (equipment)		$m^3/m^2 \cdot yr$	0.00058	0.00058
Cleaner solution 1		$m^3 /m^2 \cdot yr$	0.031	0.031
Cleaner solution 2		$m^3/m^2 \cdot yr$	0.00031	0.00082
Stripper		$m^3/m^2 \cdot yr$	0.00041	0.00054
Floor finish		$m^3/m^2 \cdot yr$	0.00016	0.00022
Clean water		$m^3 /m^2 \cdot yr$	0.00051	0.00095
Dust mops (heads/handles)	Cotton	$kg/m^2 \cdot yr$	0.0038	0.0038
	Wood	$kg/m^2 \cdot yr$	0.000020	0.000020
	Steel	$kg/m^2 \cdot yr$	0.000012	0.000012
	PVC	$kg/m^2 \cdot yr$	0.00003	0.00003
Wet mops (heads/handles)	Cotton	$kg/m^2 \cdot yr$	0.0010	0.0011
	Wood	$kg/m^2 \cdot yr$	0.000059	0.000059
	Steel	$kg/m^2 \cdot yr$	0.000037	0.000037
	PVC	$kg/m^2 \cdot yr$	0.000102	0.000102
Battery Autoscrubber	Steel	$kg/m^2 \cdot yr$	0.0057	0.0057
	Polyethylene	$kg/m^2 \cdot yr$	0.00097	0.00097
	Aluminum	$kg/m^2 \cdot yr$	0.00029	0.00029
	Rubber	$kg/m^2 \cdot yr$	0.00029	0.00029
Autoscrubber Battery	Lead	$kg/m^2 \cdot yr$	0.032	0.033
	Sulfuric acid	$kg/m^2 \cdot yr$	0.012	0.012
	Copper	$kg/m^2 \cdot yr$	0.00013	0.00014
	Glass	$kg/m^2 \cdot yr$	0.00014	0.00014
	Polythethylene	$kg/m^2 \cdot yr$	0.0010	0.0011
	Polypropylene	$kg/m^2 \cdot yr$	0.0036	0.0037
Autoscrubber Green Pads	Nylon	$kg/m^2 \cdot yr$	0.0072	0.0073
Autoscrubber Black Pads	Polypropylene	$kg/m^2 \cdot yr$	0.00009	0.00012
Burnisher	Steel	$kg/m^2 \cdot yr$	0.0036	0.0036
	Polyethylene	$kg/m^2 \cdot yr$	0.00059	0.00059
	Aluminum	$kg/m^2 \cdot yr$	0.00018	0.00018
	Rubber	$kg/m^2 \cdot yr$	0.00018	0.00018
Burnisher pads	Polyester	$kg/m^2 \cdot yr$	0.00082	0.00082
Strip mops (heads/handles)	Polypropylene	$kg/m^2 \cdot yr$	0.000018	0.000024
	Wood	$kg/m^2 \cdot yr$	0.000020	0.000020
	Steel	$kg/m^2 \cdot yr$	0.000034	0.000034
	PVC	$kg/m^2 \cdot yr$	0.000012	0.000012
Doodlebug	Polypropylene	$kg/m^2 \cdot yr$	0.000063	0.000084
Finish mops (heads/handles)	Nylon	$kg/m^2 \cdot yr$	0.00016	0.00025
	Polyester	$kg/m^2 \cdot yr$	0.000020	0.000020
	Wood	$kg/m^2 \cdot yr$	0.000012	0.000012
	Steel	$kg/m^2 \cdot yr$	0.000012	0.000012
	PVC	$kg/m^2 \cdot yr$	0.00016	0.00025
Straight broom	Nylon	$kg/m^2 \cdot yr$	0.000042	0.000042
	Wood	$kg/m^2 \cdot yr$	0.000059	0.000059
	Steel	$kg/m^2 \cdot yr$	0.000037	0.000037
	PVC	$kg/m^2 \cdot yr$	0.00010	0.00010
Putty knife	Steel	$kg/m^2 \cdot yr$	0.000020	0.000020
Scraper	Steel	$kg/m^2 \cdot yr$	0.000102	0.000102
Doodlebug	Polypropylene	$kg/m^2 \cdot yr$	0.000065	0.000087
Dust pan	PVC	$kg/m^2 \cdot yr$	0.000059	0.000059
Squeegee	Rubber	$kg/m^2 \cdot yr$	0.00023	0.00023
	Plastic	$kg/m^2 \cdot yr$	0.00070	0.00070
Buckets	PVC	$kg/m^2 \cdot yr$	0.00016	0.00016
Wringer	PVC	$kg/m^2 \cdot yr$	0.0014	0.0014
Wet floor signs	PVC	$kg/m^2 \cdot yr$	0.00010	0.00010